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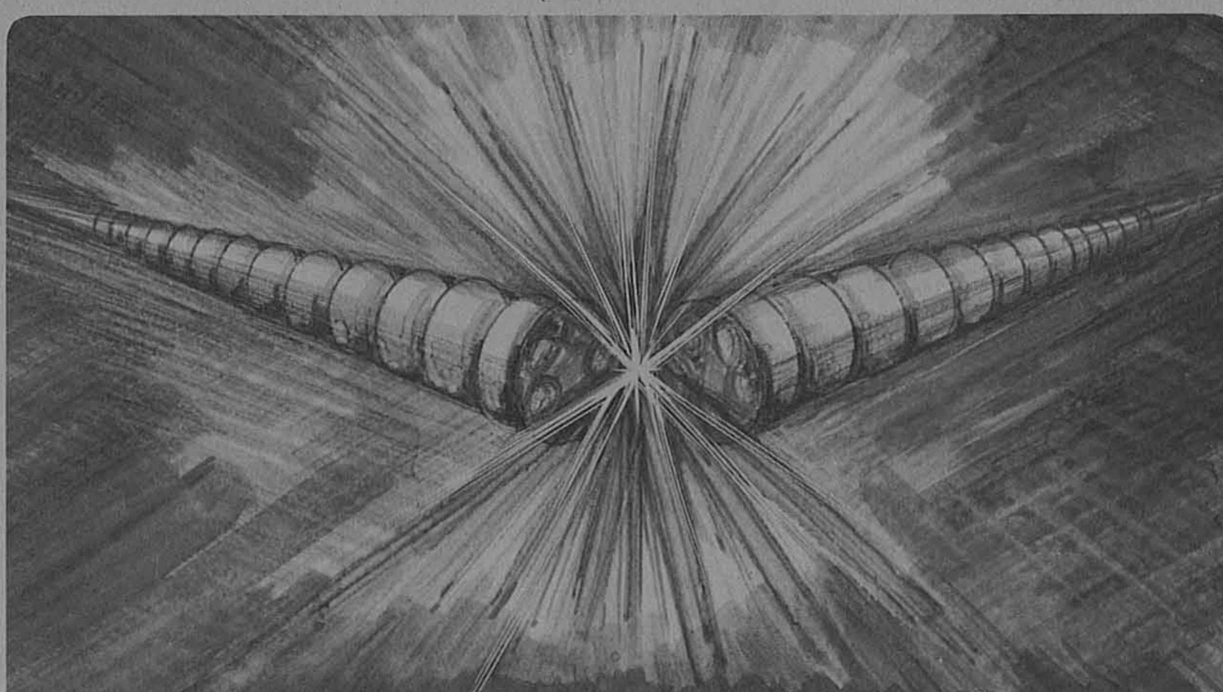

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A SURVEY OF SYNCHROTRON RADIATION DEVICES PRODUCING CIRCULAR OR VARIABLE POLARIZATION

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A survey of synchrotron radiation devices producing circular or variable polarization

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ABSTRACT

We review the properties and operating principles of the new types of synchrotron radiation devices that produce circular polarization, or polarization that can be modulated in arbitrary fashion.

1. INTRODUCTION

The characteristics of synchrotron radiation--the intensity, tunability and partial coherence--are well-known and are responsible for the construction of several advanced synchrotron radiation facilities around the world. However, the polarization capability of the synchrotron radiation has been limited due to the fact that the polarization from the usual synchrotron radiation sources, bending magnet observed in the trajectory plane, planar wigglers and undulators, is linear and fixed in direction (usually the horizontal direction). The situation will improve in the near future due to the invention of several novel types of synchrotron radiation sources that can produce circular polarization, or more generally, a polarization that can be switched between two arbitrary states. The ability to modulate polarization of intense synchrotron radiation will have an important impact in probing the structures of atoms, condensed matter and biological samples[1].

Table 1 gives an overview of the different devices producing circular or variable polarization. The devices are classified according to the usual classifications of synchrotron radiation devices; bending magnet, wiggler and undulator. In the rest of the paper, we will discuss the operating principle and the properties of each of the devices in the Table.

Classification	Devices
Bending Magnet	Observed off the trajectory plane ($x \neq 0$)
Wiggler	Asymmetric wiggler (Goulon, Elleaume, Rauox) Elliptical Wiggler (Yamamoto, Kitamura)
Undulator Devices producing helical field	Helical magnet Tilt pole undulator (Halbach) Cross overlapped undulator (Onuki) Planar-helical undulator (Elleaume) Modified planar-helical undulator (Diviacco, Walker)
Device based on interference effect	Crossed Undulator (Moissev, Niktitin, Fedorov), (Kim)

Table 1. Synchrotron Radiation Devices for Circular or Variable Polarization

2. POLARIZATION PROPERTIES OF BENDING MAGNET RADIATION

It is well known that the bending magnet radiation is elliptically polarized when observed at an angle away form the trajectory plane.[2] The components of the electric vector is given by

$$\begin{pmatrix} E_x \\ \\ E_y \end{pmatrix} \propto e^{i\Phi} \begin{pmatrix} K_{2/3}(\eta) \\ \\ \dfrac{i\gamma\psi}{\sqrt{1+(\gamma\psi)^2}} K_{1/3}(\eta) \end{pmatrix} \tag{1}$$

Here $E_x(E_y)$ is the horizontal (vertical) component, $e^{i\Phi}$ is a phase factor, γ is the electron's kinetic energy in unit of the rest energy, ψ is the vertical angle, K's are the Bessel functions, and $\eta = (\omega/2\omega_c)(1 + (\gamma\psi)^2)^{3/2}$, ω = radiation frequency and ω_c = the critical frequency. We see from Eq. (1) that the vertical component is non-vanishing when $\psi \neq 0$ and is 90° out of phase with the horizontal component, implying that the radiation is elliptically polarized. The ratio between the minor and the major axis of the polarization ellipse is given by

$$r = \frac{\gamma\psi}{\sqrt{1+(\gamma\psi)^2}} \frac{K_{1/3}(\eta)}{K_{2/3}(\eta)} \tag{2}$$

The ratio is zero for $\psi = 0$ (linearly polarized) and monotonically increases to unity (circularly polarized) for $\gamma\psi >> 1$. However, the photon flux also vanishes at large vertical angles, and the polarization cannot be completely circular.

The sense of the rotation of the elliptical polarization for $\psi > 0$ is opposite to that of the case $\psi < 0$. Therefore, the polarization can be modulated by collecting the radiation through a horizontal slit, and by mechanically moving the slit up and down with respect to the trajectory plane. The method has been used in spin resolved photoelectron spectroscopy[3].

3. WIGGLERS

3.1. Polarization properties of a planar wiggler

A planar wiggler is a sequence of short bending magnets (poles) of alternate polarities. Therefore it might be naively anticipated that it will produce intense elliptically polarized radiation in the direction $\psi \neq 0$. However, this is not so and the wiggler radiation is linearly polarized for all ψ. This is because the wiggler radiation consists of contributions from bending sections of the positive polarity and those from the negative polarity. The electric field from the positive poles is of the form given by Eq. (1), while that from the negative poles is given by

$$\begin{pmatrix} E_x \\ \\ E_y \end{pmatrix} \propto e^{-i\Phi} \begin{pmatrix} K_{2/3}(\eta) \\ \\ \dfrac{-i\gamma\psi}{\sqrt{1+(\gamma\psi)^2}} K_{1/3}(\eta) \end{pmatrix} \tag{3}$$

Adding these two contributions, we find

$$\begin{pmatrix} E_x \\ \\ E_y \end{pmatrix}_{\text{wiggler}} \propto \begin{pmatrix} \cos(\Phi)\, K_{2/3}(\eta) \\ \\ \dfrac{\sin(\Phi)\, \gamma\psi}{\sqrt{1+(\gamma\psi)^2}}\, K_{1/3}(\eta) \end{pmatrix} \tag{4}$$

Thus, the horizontal and the vertical components are in phase, implying that the polarization is linear.

The direction of the polarization, however, does not in general lie in the horizontal direction when $\psi \neq 0$. The direction depends on Φ, which varies rapidly as a function of the frequency or the angle ψ. On the average, the radiation appears to have a net unpolarized component, the electric vector being randomly distributed along the polarization ellipse corresponding to a single pole.

3.2. Asymmetric wiggler

The linear polarization of the radiation from planar wiggler is due to the symmetry of the electron trajectory in a half-period section of positive pole with that in the adjacent half-period of negative pole. The symmetry can be broken by arranging the magnets of opposite poles to have different strengths and lengths, such as the one schematically shown in Fig. 1. This so-called asymmetric wiggler was proposed by Goulon, Elleaume and Rauox[4], and is being installed at Super ACO at Orsay and HASYLAB at Hamburg.

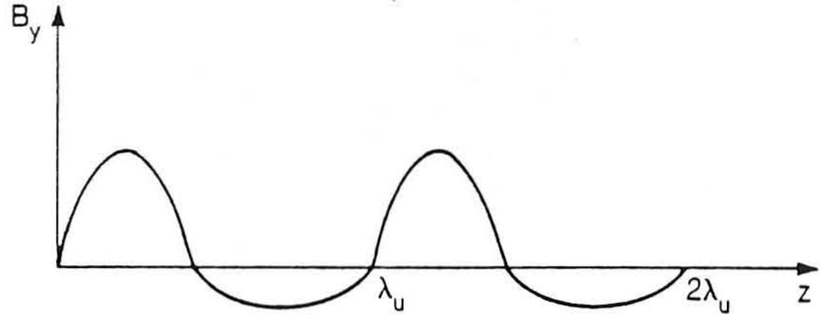

Figure 1. A schematic of magnetic field configuration for the asymmetric wiggler. The field integral within each period must vanish.

3.3. Elliptical wiggler

An elliptical wiggler, first proposed by Yamamoto and Kitamura[5], is an arrangement of periodic magnets such that the electron trajectory is given by

$$\begin{aligned} x &= a \cos(2\pi z/\lambda_w) \\ y &= b \sin(2\pi z/\lambda_w) \end{aligned} \tag{5}$$

where x, y and z are, respectively, the coordinates in the horizontal, vertical, and longitudinal directions, λ_w is the wiggler period. In a planar wiggler or undulator, b = 0, while in a helical undulator a = b. An elliptical wiggler, in which a >>b, consists of two overlapping wigglers, one producing a strong vertical magnetic field producing the x-motion and one producing a weak horizontal field producing the y-motion.

As the motion in x–y plane is elliptical, it is clear that the radiation will be elliptically polarized. The trajectory is made elliptical rather than circular in order to obtain short wavelength, higher harmonic radiation in the forward direction; as is well known, for a helical trajectory, a = b, the radiation in the forward direction contains only the fundamental harmonic wavelength.

A better way to understand the radiation from the elliptical wiggler is to approximate the trajectory by a three-dimensional sinusoidal curve, in which the adjacent half-periods lie on different planes, as illustrated in Fig. 2. The radiation emitted from the point B has the same complex amplitude, given by Eq. (1), as that from the point A. This is because the sense of rotation as well as the observation angle ψ at point B are opposite to those at point A.

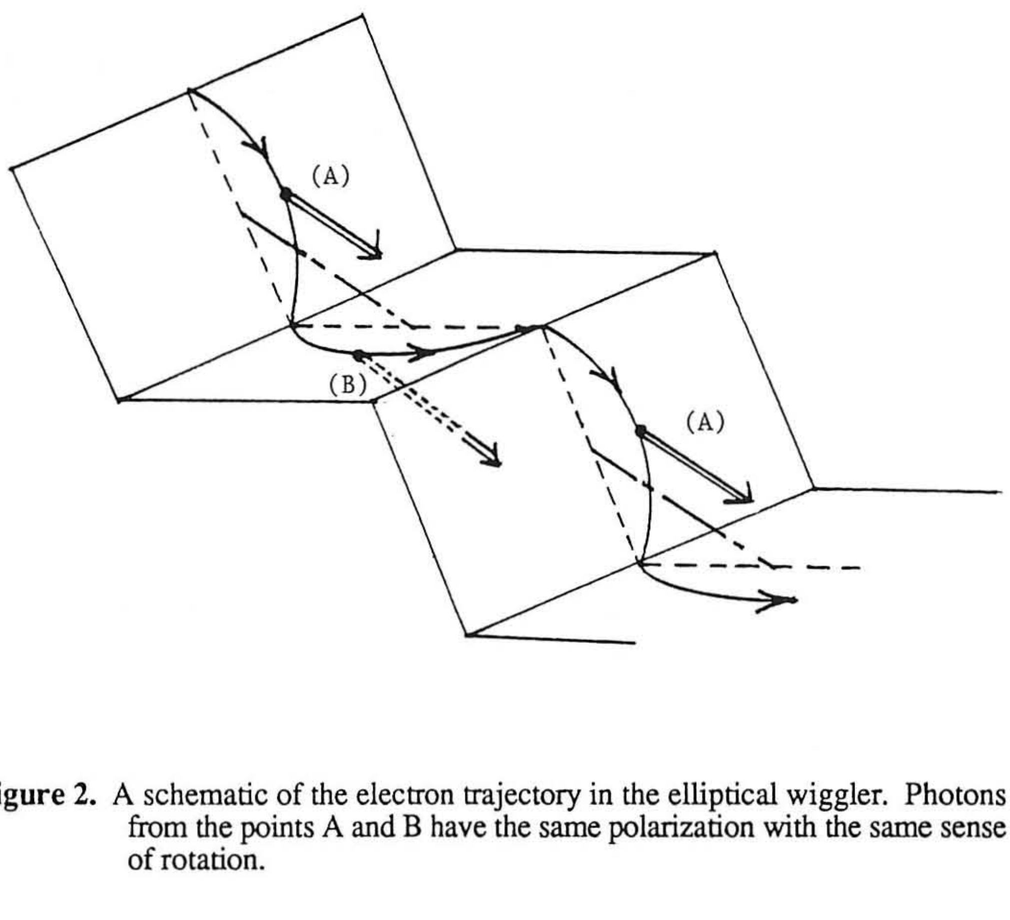

Figure 2. A schematic of the electron trajectory in the elliptical wiggler. Photons from the points A and B have the same polarization with the same sense of rotation.

The sense of the polarization ellipse in this device can be reversed mechanically by moving the magnet producing the y-motion. In practice, this is rather slow because the vertical gap must first be opened in order to reduce the strong magnetic force acting on the magnet blocks.

The elliptical wigglers are installed in photon factory and in the Tristan booster at KEK to produce intense, elliptically polarized radiation of very short wavelengths[6].

4. UNDULATORS

Undulators produce brighter radiation than wigglers because the radiation is contained in a narrower angular cone and in a few narrow spectral peaks[2]. Undulators for circularly polarized radiation can further be classified into two groups: the first one produces helical magnetic fields, and is referred to as the helical undulators, and the second one is based on the interference effect.

4.1. Helical undulators (producing helical magnetic field)

The trajectory in a helical undulator is of the form given by Eq. (5), with $a = b$, giving rise to circularly polarized radiation. Unlike in the case of the planar undulator ($b = 0$) or the elliptical wiggler ($b << a$), a helical undulator produces only fundamental harmonic in the forward direction. Thus helical undulator is in general more useful for low energy applications.

4.1.1. Helical magnet

Electromagnetic helical undulator using bifilar coil windings is well-known. A permanent magnet helical undulator consists of short segments of dipole magnets, each of which is rotated by a fixed angle Θ relative to the previous one[7]. Although elaborate, it should be possible to design a magnetic structure with variable Θ, hence of variable period. However, the sense of the rotation cannot be reversed without passing through a pure dipole configuration and therefore losing particles.

4.1.2. Tilt-pole undulator

A planar undulator whose pole boundaries are tilted from a right angle with respect to the axial direction can be used as a helical undulator because the magnetic field in a plane at a certain vertical distance from the horizontal mid-plane of the undulator contains helical components[8]. It also contains field in the z-direction. It is expected that the effects of such field will be small for high energy electrons. However, a complete analysis of the field and the particle motion for this device has not been carried out yet.

4.1.3. Cross overlapped undulator

Onuki[9] proposed a magnet arrangement in which two identical undulators in perpendicular directions are overlapped to produce a helical field on axis. The polarization in this device can be adjusted arbitrarily by mechanically changing the relative phase between two undulators, similar to the case of the crossed undulator to be discussed later (see Fig. 4.). A proof-of-principle structure has been built and tested at ETL, Japan.

4.1.4. Planar-helical undulator

Both the helical magnet and the cross overlapped undulator have the drawback that the vacuum chamber dimensions are restricted both in the horizontal as well as in the vertical direction. Elleaume proposed a scheme whose mechanical structure is similar to that of the conventional planar undulator[10]. The device is therfore referred to as a planar-helical undulator. The idea is to arrange the magnet blocks in the top jaw to produce the horizontal field and those in the bottom jaw the vertical field. Fig. 3 gives a possible such arrangement of permanent magnet blocks. By following the magnetic field lines, it is easy to see that the top jaw produce a periodic horizontal field, and the bottom jaw a periodic vertical field. By adjusting the relative longitudinal position of the two jaws, it will be possible to modulate the polarization arbitrarily, as in the case of the cross-overlapped undulator.

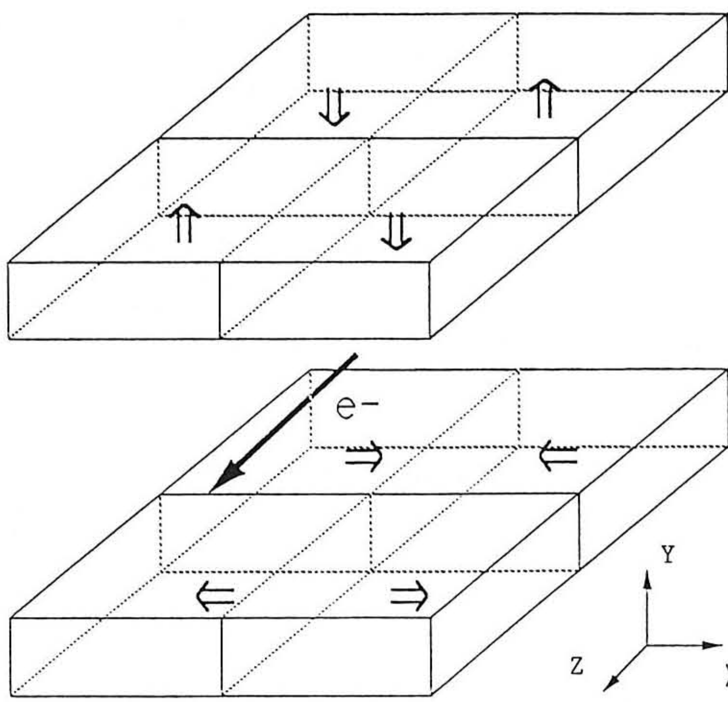

Figure 3. The magnet block arrangement in the planer-helical undulator. Only one period of top and bottom jaw are shown.

The achievable field in planar-helical undulator is weaker than that of the helical magnet. However, the fact that the structure can accommodate wide vacuum chamber in the horizontal direction is a significant advantage.

The planar-helical undulator produces a net orbit deflection, which could be significant for low energy (1 – 2 GeV) synchrotron radiation rings[11]. However, the effect is negligible for high energy machines (≥ 5 GeV). The device is planned to be installed at ESRF.

4.1.5. Modified planar-helical undulator

Diviacco and Walker proposed a structure in which the top and bottom jaws are similar, each jaw producing its own helical field on axis[11]. Each jaw is made of half periods taken alternatively from the top and bottom jaw of Fig. 3. This structure does not suffer from an orbit deflection. On the other hand, the polarization cannot be modulated.

4.2. Crossed undulator

A crossed undulator is an arrangement of two undulators oriented at 90° with respect to each other, as illustrated in Fig. 4. Unlike the cross-overlapped undulator, the two undulators are separated axially. Electrons oscillate in the x-direction in the first undulator, emitting photons linearly polarized in the x-direction. The radiation from the second undulator, on the other hand, is polarized in the y-direction. When observed through a monochromator, the combined radiation is elliptically polarized, the polarization ellipse being determined by the electron path length between the two undulators. The idea was proposed by Moissev, Nikitin and Fedorov[12], and independently by Kim[13].

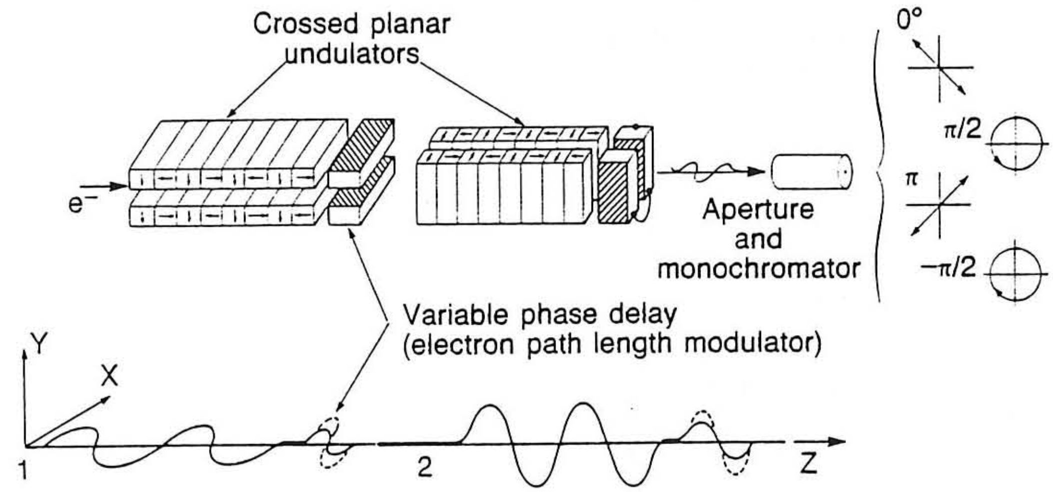

Figure 4. A schematic of the crossed undulator. The shaded block is the modulator.

Let E be the field amplitude due to the first undulator. The field amplitude due to the second undulator is the same as that due to the first except for a phase factor. The total field vector is given by

$$E_T = E\,(\mathbf{e}_x + e^{i\phi}\mathbf{e}_y), \tag{6}$$

where $\mathbf{e}_x(\mathbf{e}_y)$ is the unit vector in the x(y) direction. The phase ϕ is given by

$$\phi = \frac{2\pi}{\lambda}\left(\frac{L_c}{\beta} - L\right). \tag{7}$$

Here λ = radiation wavelength, β = electron speed/light speed, L_c = the arc length of the electron trajectory from the beginning of the first undulator to the beginning of the second undulator, and L = the straight distance from the beginning of the first undulator to the beginning of the second undulator. From Eq. (7) we derive that

$$\phi \approx \frac{2\pi}{\lambda}\frac{1}{2}\int_0^L dz\left(x'^2 + \frac{1}{\gamma^2}\right). \tag{8}$$

Here x' is the angle between the electron trajectory and the z-direction.

The phase ϕ determines the polarization. For example, when $\phi = 0$, the polarization is linear at an angle 45° with respect to the x-direction. On the other hand, when $\phi = \pi/2$, the radiation is circularly polarized. The polarization can be modulated mechanically by changing the distance between two undulators (by about the length of the undulator period, as follows from Eq. (8)). More conveniently, the polarization can be modulated electromagnetically by introducing a short AC magnet, called the modulator, between two undulators. The varying magnetic field modulates the x'^2 – term in Eq. (8), and hence the phase.

The ability to modulate the polarization arbitrarily is similar to the case of the cross-overlapped undulator and the planar-helical undulator discussed before. However, the modulation of the crossed undulator can be done electromagnetically, and therefore is in principle more versatile.

Historically the crossed undulator was the first to be proposed among the various variable polarization devices discussed in this paper (except, of course, the use of the off-plane bending magnet). The idea of using modulator was proposed in ref. 13.

The operation of the crossed undulator depends upon the interference phenomena. One might wonder how the radiation from the first undulator can interfere with that from the second undulator, which is separated in time from the first one. The answer is that one is observing a single frequency component of the radiation by means of a monochromator. A monochromator stretches the radiation pulses in the axial direction so that the contributions from two undulators overlap in time after the monochromator.

From Eq. (8), we can see that angular divergence of electron beam causes a blurring of the phase ϕ, leading to depolarization effect. Therefore a satisfactory performance of cross undulators requires a low emittance electron beam, particularly for short wavelength radiation. A crossed undulator is being constructed at BESSY, Berlin. Another one is being proposed for Aladdin as a multi-laboratory collaboration. These devices will produce variably polarized undulator radiation in the photon energy range between 10 and 100 eV.

5. CONCLUSIONS

In this paper, we have described various synchrotron radiation devices that produce polarization which is circular or can be modulated arbitrarily. Many of these devices are either installed or being built. Thus we can expect significant progress in the near future in the technology of constructing such devices and in using them for scientific experiments.

6. ACKNOWLEDGEMENTS

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